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A METHOD FOR THE MEASUREMENT OF SOUND INTENSITY.

By J. C. Karcher.

ABSTRACT.

A sound-detecting device, such as a magnetophone or electrostatic transmitter, and two coils whose mutual inductance can be varied by known amounts constitute a measuring instrument. The sound detector and one coil are connected to an indicating instrument, consisting of a vacuum-tube amplifier, a rectifier, and galvanometer. The emf generated in the detecting instrument is compared by substitution with emf generated in one coil when the other carries a known current. Since the sound intensity is proportional to the square of the emf generated in the detector, a means of making sound-intensity measurements is presented. The necessity for the calibration of an amplifier is obviated. The instrument has a sensitivity range of about a millionfold.

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I. INTRODUCTION.

The intensity of sound, either relative or absolute, has been measured in a variety of ways. Among the many ways might be mentioned the classical method, wherein the intensity is determined directly by the use of a Rayleigh disk.[1] This method requires the presence of the observer, suitably housed, in the vicinity of the point at which measurements are being made. Wien's [2] and Webster's [3] "phones" have been successfully used for the measurement of absolute and relative sound intensity. These devices also require the near-by presence of the observer. A more recent device for the measurement of absolute and relative sound intensity is described by Wente [4] and entails the use of a condenser, transmitter, and an amplifier.

[1] W. Konig, Wied. Ann., 43, p. 51; 1891; Lord Rayleigh, Theory of sound, 2, pp. 44, 45.
[2] M. Wien, Phys. Zeitschr., 13, p. 1034.
[3] A. G. Webster, Nat. Acad. Sci. Proc., 5, pp. 173, 275; 1919.
[4] E. C. Wente, Phys. Rev. (2), 19, p. 498; 1922.

The first of these methods has been used by Prof. F. R. Watson[5] in the determination of the acoustical properties of building materials.

Another method that has been successfully used in the study of acoustical properties of building materials is that of Professor Sabine,[6] wherein the rate of decay of sound intensity is determined. Although the results of the application of this method by Prof. W. C. Sabine and Dr. Paul E. Sabine[7] probably represent the greatest accomplishment in the study of architectural acoustics by any single method, it is felt that with the advent of the vacuum tube as a generator of alternating current and as an amplifier more satisfactory means for measuring sound intensity are available.

II. SOME FEATURES WHICH ENTER INTO THE MEASUREMENT OF SOUND INTENSITIES.

When it is desired to make sound measurements in a room, in the neighborhood of a sound source, or in any other kind of sound field, because of the large absorbing power of an observer he should be remotely located. The measuring or exploring instrument should be small and practically nonabsorbing.

The measuring instrument must be rugged and easily operated and should retain its calibration over a long period or be easily calibrated, particularly when an extended series of measurements is contemplated. A wide range of sensitivity is necessary because of the great range of sound intensities likely to be measured, and remote observation and control of all sound producing and measuring apparatus is desirable.

With a view to meeting some of these requirements, the apparatus, which will be described, has been constructed and placed in operation.

III. DESCRIPTION OF APPARATUS.

The sound producer used is that described by E. A. Eckhardt.[8] The grid current for two 5-watt vacuum tubes is derived from a vacuum-tube oscillator, and the output of the two tubes, which we will call the generator, is used to drive a Magnavox "loud speaker" (large size). A Hartley circuit is used for the oscillator instead of that described by Eckhardt, as it gives good

[5] F. R. Watson, Eng. Exp. Sta., Univ. of Ill. Bull. No. 127.
[6] W. C. Sabine, Collected papers on acoustics.
[7] P. E. Sabine, Phys. Rev., 16, p. 514; 1920, etc.
[8] E. A. Eckhardt, Phys. Rev , 17, p. 380; 1921.

wave form over a wider range of frequencies. The output for a chosen frequency was kept constant by adjusting the field current and the alternating current through the loud speaker. This alternating current is led through a 100-turn coil *A* (fig. 1) on the comparator of the sound-measuring apparatus.

The sound-measuring apparatus (fig. 1) consists of a magnetophone *P*, which is connected to the first grid circuit of a 4-stage reactance-coupled amplifier *M*, so arranged that 0 to 4 stages may be used. The output is connected through a transformer to a molybdenite crystal rectifier *D* and a high sensitivity galvanometer *G*, with lamp and scale. There is connected in series with the magnetophone a 1,250-turn coil *B* about 7 cm average diameter and of rectangular cross section. A "duolateral" 1,250-turn radio coil is used. This coil is mutually coupled to the 100-

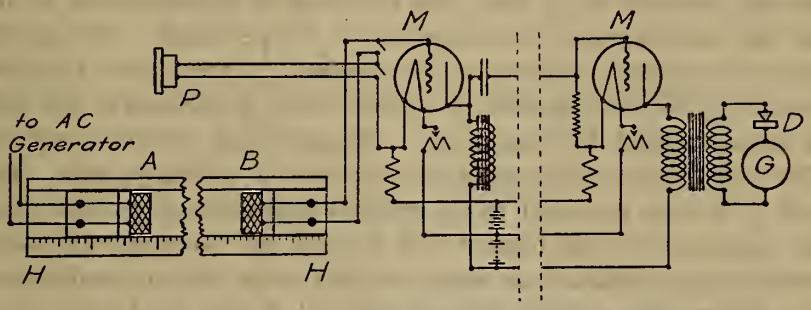

FIG. 1.—*Schematic diagram of sound intensity measuring apparatus.*

turn coil *A*, which is connected in the alternating-current circuit of the loud speaker. These coils are mounted on suitable supports.

The 1,250-turn coil is placed at one end of a graduated guide *H*, and the 100-turn coil is free to slide along the guide so that the axes of the two coils are coincident. In this way when there is alternating current in the small coil the induced voltage in the large coil may be varied by moving the small coil along the guide. This device, which is similar to that used by Prof. L. V. King[9] in his study of telephone receivers, will be referred to later as the comparator.

All of the measuring apparatus, with the exception of the magnetophone *P*, is set up in a laboratory which is adjacent or near to the "sound chamber." A flexible pair of wires extends from the magnetophone, which is placed in the sound chamber, to the laboratory. The comparator is placed 2 or 3 m away from any metal sheets or frames.

[9] L. V. King, Journ. Frankl. Inst., May, 1919.

The measurement of sound intensity at the magnetophone is made by a comparison of the emf E_p generated in the magnetophone, due to its presence in the sound field, with the emf E_B which is induced in the 1,250-turn coil by the mutual coupling with the coil A. The comparison is made by substitution. This is much easier to do than to balance the emf's, since, in general, as the exploring magnetophone is moved through the sound field, there is a different phase for each position.

When it is desired to make a measurement, the coil A is turned at right angles to coil B and removed to the farther end of the comparator scale. The sound source is started and the amplifier is so adjusted that a deflection of from 20 to 30 cm is obtained with the high sensitivity galvanometer G. Since this deflection is nearly proportional to the sound intensity and as the scale can readily be read to ½ mm, the precision of measurement as far as the galvanometer is concerned is ¼ per cent. The galvanometer reading is taken to the nearest ½ mm, then the field circuit of the loud speaker is opened, and, if necessary, the field is demagnetized by means of a rheostat and reversing switch. The galvanometer deflection will return to o within ½ mm. The coil A is then returned to its original position and moved along the graduated guide toward coil B until the same galvanometer deflection is obtained as was obtained with the magnetophone. The alternating current through the coil A and the Magnavox is kept constant during these measurements. The distance between the center of the two coils is read from the graduations on the guide of the comparator.

IV. CHARACTERISTICS OF APPARATUS.

We will note that the emf E_B which is generated in the coil B, due to presence of coil A, which carries a constant alternating current I_A, is given by the relation

$$E_B = 2\pi f M I_A$$

where

f = frequency of the alternating current.

M = mutual inductances between coils A and B.

E_B and I_A = effective values of voltage and current, respectively.

Also, we have the relation

$$E^2_p = KU$$

where

E_p = emf generated in the magnetophone due to its presence in the sound field.

U = sound intensity at the magnetophone.

K = constant of the magnetophone.

When the comparison is made, M is so adjusted that $E_D = E_B$, then, by substitution

$$K\,U = 4\pi^2 f^2 M^2 I^2_A$$

or for a given series of measurements at constant frequency and current.

$$U = K'\,M^2.$$

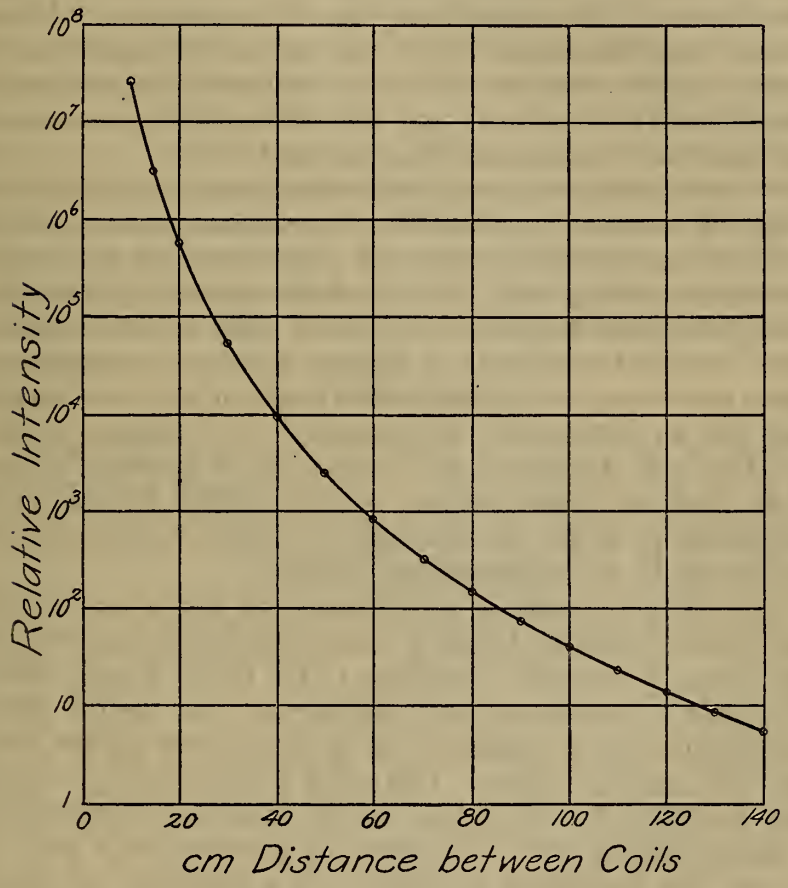

FIG. 2.—*Typical calibration curve.*

Now, it is only necessary to determine the value of M for the observed setting of the coil A in order to determine the relative value of U. It is, of course, much more convenient to plot a curve using values of M^2 or relative intensity as ordinates and coil settings as abscissas and then the relative value of U for any coil setting may be read directly from the curve. Such a curve is shown in Figure 2.

The values of M were determined for the coils A and B from formulas and tables for the calculation of mutual and self inductance by Rosa and Grover;[10] formulas (5) and (6), known as Maxwell's formulas, were used. Semilogarithmic paper was used for the graphs. Distances between coils were plotted as abscissas, and relative intensities were plotted on the logarithmic ordinates. The maximum and minimum relative intensities that can be measured with the comparator as now used differ by a factor of 10^6. The comparator scale is 140 cm long. If one assumes that the position of the coils on the comparator can be read to 0.1 mm when the coils are 10 cm apart, the precision of measurement is $\frac{1}{2}$ per cent, and when the coils are 140 cm apart the precision of measurement is $\frac{1}{20}$ per cent.

We have used a magnetophone because it does not require any polarizing currents or potentials. A telephone receiver of the S. G. Brown type with micrometer adjustment and air damped diaphragm is being used. For the measurements of relative intensity at a given frequency, such as are made in order to determine acoustical coefficients of building materials, the magnetophone serves very well, as any desired length of lead wires may be used and no adjustments are necessary. For absolute calibration this type of magnetophone would not be desirable because of its resonance characteristics. An electrostatic transmitter or magnetophone of the type described by Hewlett [11] can readily be substituted for the magnetophone described.

The rectifying couple is a permanent one and is made up in the following manner: A flake of molybdenite about 0.3 mm thick and 8 mm in diameter is soldered to the top of a brass block. This block is attached to one binding post. On the top of the molybdenite flake is attached a bit of solder about 0.5 mm thick and 2 or 3 mm in diameter. One end of a spiral of No. 40 copper wire is embedded in this solder and the other end is attached to a second binding post. The whole is mounted on a piece of bakelite and the crystal is covered with a protecting cap, much after the fashion of mounting thermocouples. Fresh, cleaned surfaces of molybdenite will adhere to clean lead-tin solder when the solder is heated just sufficiently to flow easily. As such couples do not always rectify, it is well to make up a number and select one from these. The couple which is now being used has been used in laboratory work for more than a year and has

[10] B. S. Sci. Paper No. 169.

[11] C. W. Hewlett, Phys. Rev. (2), 19, p. 52; 1922.

maintained its calibration during that time. Alternating currents as small as 10^{-8} amperes can be measured with the aid of a highly sensitive galvanometer. The calibration curve is similar to that of a thermocouple.

Because of the shape of curve obtained in the calibration of the molybdenite couple the galvanometer deflections for a given adjustment of the amplifier will be proportional to the sound intensity. Consequently, when it is desired to make a series of observations rapidly, this can be done at a small sacrifice in accuracy in the following way: Adjust the amplifier so that the desired galvanometer deflection is obtained, then with the sound source cut off adjust the coil A until a chosen galvanometer deflection is obtained. By noting the position of the coil A and referring to the comparator calibration curve the relative sound intensity corresponding to the chosen galvanometer deflection will have been determined. For other deflections the intensities will be in proportion. When used in this way, the comparator is merely a convenient device for calibrating the amplifier and galvanometer.

V. CONCLUSIONS.

The novel features of the apparatus are that a single instrument has a relative intensity range of 1 to 1,000,000, with the lower limit near the threshold value of audibility, and that the precision of measurement increases rather than decreases with decrease of intensity. A commendable feature is that the elements of the apparatus which enter into the calibration consist of two coils, a scale, and magnetophone. The alternating-current ammeter, which measures the comparison current in coil A, enters into the calibration, but when used with an electrical source of sound, as is here done, the alternating current which passes through the coil A also drives the loud speaker. Therefore, if there is an error in the value of the current I_A the resulting percentage of error in E_B is the same as the resulting percentage of error in E_p. Consequently, the resulting error in measurement of U is of the second order of smallness.

Absolute standardization of the apparatus may be effected by comparison with a Rayleigh disk or by the use of a thermophone.[12]

WASHINGTON, February 1, 1923.

[12] Arnold and Crandal, Phys. Rev , 10, pp. 22, 52; 1917.